

# Comments on “First Dark Matter Results from the XENON100 Experiment”

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The XENON100 collaboration has recently released new dark matter limits [1], placing particular emphasis on their impact on searches known to be sensitive to light-mass (below  $\sim 10$  GeV/ $c^2$ ) Weakly Interacting Massive Particles (WIMPs), such as DAMA [2] and CoGeNT [3]. We describe here several sources of uncertainty and bias in their analysis that make their new claimed sensitivity presently untenable. In particular, we point out additional work in this field and simple kinematic arguments that indicate that liquid xenon (LXe) may be a relatively insensitive detection medium for the recoil energies (few keV<sub>r</sub>) expected from such low mass WIMPs. To place the discussion that follows in some perspective, using the most recently suggested mean value of the galactic escape velocity [4], an example 7 GeV/ $c^2$  WIMP can impart an absolute maximum of 4 keV<sub>r</sub> to a xenon nucleus, with the majority ( $\sim 90\%$ ) of the events depositing energies below 1.5 keV<sub>r</sub>.

It is suggested in [1] that the value of  $\mathcal{L}_{\text{eff}}$  (the ratio between electron equivalent energy and nuclear recoil energy) adopted to obtain WIMP limits is constant ( $\mathcal{L}_{\text{eff}} \sim 0.12$  below  $\sim 10$  keV<sub>r</sub>) and a representative compromise encompassing all existing low-energy measurements for LXe<sup>1</sup>. Nothing is further from reality.

Attempts to measure  $\mathcal{L}_{\text{eff}}$  can be classified into two methods [5], fixed-energy neutron experiments with scattered neutron tagging like those exclusively considered by XENON100, and direct comparisons between broad-spectrum neutron source calibration data and a variety of Monte Carlo simulations, like those adopted by the ZEPLIN collaboration [6]. Results from the latter are included as the red band in Fig. 1 here, displaying the dramatic drop in  $\mathcal{L}_{\text{eff}}$  observed at recoil energies that would make a LXe search for light WIMPs a futile exercise. Interestingly, a drop in response to low energy recoils seems to be a common feature to all other attempts to use the second method (Fig. 2) [7], including the most recent by

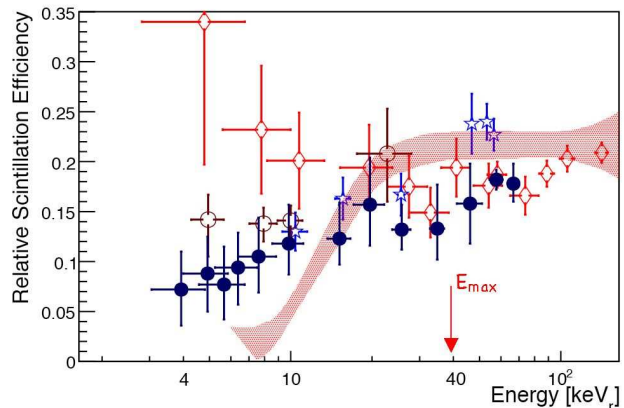


FIG. 1: Measurements of  $\mathcal{L}_{\text{eff}}$  in LXe. The red vertical arrow indicates the calculated value for the kinematic cutoff in recoil energy (see text). The most recent analysis by the XENON10 collaboration [8], not considered in [1], follows the same trend as in Manzur *et al.* [5] (dark blue points here). Light-mass WIMPs like those claimed to be excluded in [1] concentrate their signal beyond the left margin of this figure. A constant  $\mathcal{L}_{\text{eff}} \sim 0.12$  below  $\sim 10$  keV<sub>r</sub> is used in [1] to obtain dark matter limits.

the XENON10 collaboration [8]. This last, not shown in these figures, is a reanalysis of [9]. None of this is mentioned in [1], where the authors repeatedly refer to their selective list of measurements as “all data”.

While virtues and defects can be listed for both methods, a common feature of most of these measurements is the value of  $\mathcal{L}_{\text{eff}}$  (few tens of keV<sub>r</sub>) at which the drastic drop in recoil sensitivity appears. This onset and ensuing trend is also visible in the data from [5], the most recent fixed-energy experiment, featuring the best control of systematics so far for that particular family of  $\mathcal{L}_{\text{eff}}$  measurements. Historically speaking, the evolution of fixed-energy experiments has proceeded monotonically towards pointing to modest recoil response at the lowest energies, i.e., towards reconciliation with broad-spectrum calibrations. This is a fact hidden from view in [1] and that clashes with their choice of  $\mathcal{L}_{\text{eff}}$  (Fig. 1). Most researchers in the field will argue that this behavior (null  $\mathcal{L}_{\text{eff}}$  at zero or small recoil energy) is to be naturally expected. Next we provide at least one physical mechanism supporting this.

The marked drop in  $\mathcal{L}_{\text{eff}}$  at low energies in the experiments that the XENON100 collaboration has ignored may be understood from simple two-body kinematics af-

[1] In a fascinating attempt at *trompe l’oeil*, an arbitrary monotonically decreasing  $\mathcal{L}_{\text{eff}}$  is plotted in Fig. 1 in [1], but is nowhere else used. Given the lack of agreement between the closing paragraph, the Fig. 1 caption and the phrase immediately above Fig. 2, we are led to believe that the lower 90% contour is missing from Fig. 1 below 5 keV<sub>r</sub>. This can mislead the reader to identify this contour with the extrapolation to Manzur *et al.* shown in that figure. In version 2, without truly clarifying this standing issue, the authors now explicitly mention the effect of a decreasing  $\mathcal{L}_{\text{eff}}$  below 5 keV<sub>r</sub>, resulting in much less conflict with DAMA and CoGeNT. We illustrate exactly by how much in Fig. 5 here.

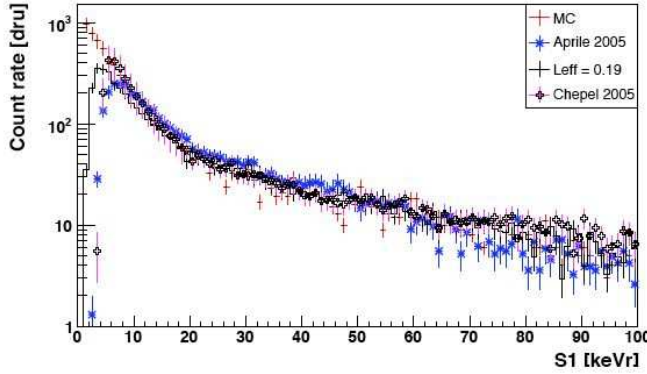


FIG. 2: Examples of comparisons between simulation (MC) and response of LXe chambers to neutron sources [7] (see text). The dramatic disagreement at few  $\text{keV}_r$  can be alleviated to some extent via trigger efficiency corrections, but not completely [8].

fecting the energy transfer from a xenon recoil to an atomic electron. As already discussed within the context of the MACRO experiment [10], a kinematic cutoff to the production of scintillation is expected whenever the minimum excitation energy  $E_g$  of the system exceeds the maximum possible energy transfer to an electron by a slow-moving recoil ( $E_{max}$ ). Unfortunately, such a basic consideration is often not included in attempts to develop an understanding of scintillator response to very slow ions [11], but this is not always the case [12]. In practice, and for the reasons described in [10], a smooth adiabatic drop is observed rather than a step-like cutoff. While it is widely acknowledged that much is left to be understood about the exact mechanisms leading to scintillation from low-energy ions in LXe (per se an obvious reason to act very conservatively), direct atomic excitation is known to compete with the recombination of ionized electrons in producing scintillation. Even then, the initial ratio of excitons to electron-ion pairs is estimated by a faction of workers in this field to be small at 0.06-0.2 [5, 13]. It would then be reasonable to identify  $E_g$  with the band gap in LXe (9.3 eV), and to expect this cutoff and the smooth decrease in  $\mathcal{L}_{eff}$  below it to appear at a calculated  $E_{max} \sim 39 \text{ keV}_r$  for LXe. We remark that this value is in good agreement with the behavior noticed in the family of  $\mathcal{L}_{eff}$  measurements disregarded by XENON100 (Figs. 1,2) and with the evident trend most recently observed in [5, 8, 14].

Fig. 3 displays approximate values for  $E_{max}$  for other scintillators used in dark matter research, calculated following [10, 15, 16]. While the measurements of quenching factor or relative scintillation efficiency (similar in meaning to  $\mathcal{L}_{eff}$  for purposes of this discussion) displayed in Fig. 3 are just a few representative examples, they span the range of energies explored in recoil calibrations up until now [11]. The comparatively large value of  $E_{max}$  for LXe is a result of its large recoil mass and relatively high  $E_g$ . It is interesting to observe that the recoil energy range well below  $E_{max}$  has only been experimentally explored for LXe and plastic scintillator (NE-110) [10], and

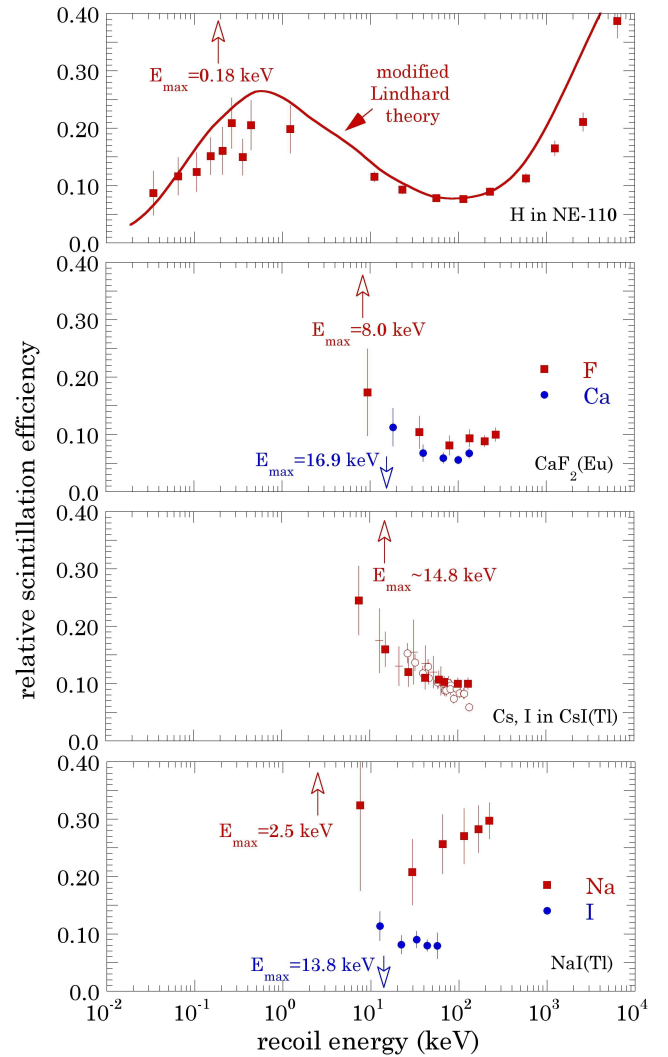


FIG. 3: Examples of measurements of quenching factor for different scintillators, indicating in each case the calculated value for the kinematic cutoff in recoil energy (see text). An additional value of  $E_{max} = 2.2 \text{ keV}_r$  is found for carbon recoils in organic scintillator, in good agreement with [12].

that in both instances the expected drop in sensitivity is readily observed at the predicted onset. This brings up a parallel observation that the low-energy trend in quenching factor for recoils in NaI(Tl) scintillators is also an experimental unknown: if the quenching factor rises before reaching  $E_{max}$ , a expected behavior [11] observed for the materials in Fig. 3 and for liquid scintillator [12], this could have important implications for light WIMP interpretations of the DAMA annual modulation, and in particular its agreement or not with CoGeNT.

There are several other weaknesses in the reasoning leading to the claims in [1]. For instance, the new claimed XENON100 limits depend critically (by several orders of magnitude below  $\sim 10 \text{ GeV}/c^2$ ) on the assumption of a Poisson tail in the modest number of photoelectrons that would be generated by a light-mass WIMP above detec-

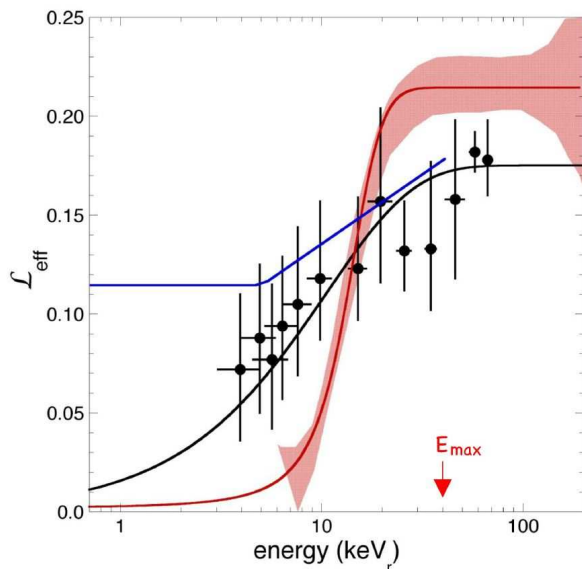


FIG. 4: Models for  $\mathcal{L}_{\text{eff}}$  used to generate the exclusions in Fig. 5. The blue line corresponds to the extrapolation to low energy used in [1]. Black points are recent data from Manzur *et al.* [5]. The black line is an adiabatic fit to these (see text). The red line (logistic fit) and band correspond to ZEPLIN data [6] (see text).

tion threshold, even for their forced choice of  $\mathcal{L}_{\text{eff}}$ . We question the wisdom of this approach when the mechanisms behind the generation of *any* significant amount of scintillation are still unknown and may simply be absent at the few  $\text{keV}_r$  level. To put it bluntly, this is the equivalent of expecting something out of nothing. An example of the level of sensitivity expected from XENON100 in the absence of this assumption can be found in [17]: WIMPs with a mass lower than  $\sim 12 \text{ GeV}/c^2$  are then entirely out of reach for XENON100, imposing no significant constraints on DAMA, CoGeNT, or any other dark matter detector technology with demonstrated sensitivity to this mass region.

It seems clear that sufficient knowledge on the energy dependence of  $\mathcal{L}_{\text{eff}}$  in the region 0-3  $\text{keV}_r$  is presently absent for LXe at the excellent level that would be required to establish reliable light-WIMP limits. This begs comparison with highly linear detecting media such as germanium detectors, for which careful dedicated measurements of quenching factor have been made down to  $\sim 0.25 \text{ keV}_r$ , measurements found to be in good agreement with theory [18, 19].

In conclusion, we find that the choice made in [1] in relation to the low-energy trend for  $\mathcal{L}_{\text{eff}}$ , a constant value below 10  $\text{keV}_r$ , is not only biased (clashing with several ignored experimental measurements and the observed historical trend), but also seemingly unphysical, as would be derived from simple kinematic considerations. We detect an intent in [1] to avoid considering important standing issues in this area of research, as well as serious contradictions around the meaning and content of their Fig. 1. We firmly maintain that the low-mass

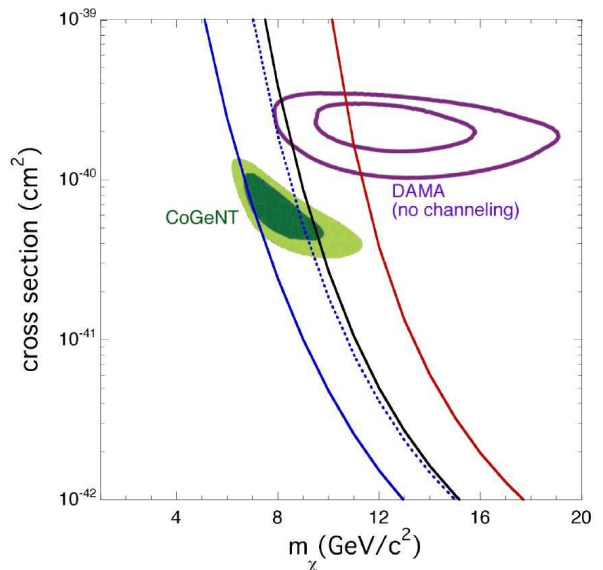


FIG. 5: XENON100 exclusions generated from the  $\mathcal{L}_{\text{eff}}$  models in Fig. 4. (same color coding). The dotted blue line corresponds to the problematic  $\mathcal{L}_{\text{eff}}$  contour in Fig. 1 in [1], ambiguously claimed by XENON100 to be both a 90% lower C.L. to their  $\mathcal{L}_{\text{eff}}$  best fit and an extrapolation to Manzur *et al.* [5], a crucial point we contend is misleading. Ion channeling is not included neither for CoGeNT nor DAMA regions [20, 21]. The low-energy trend expected for the quenching factor in NaI(Tl) [11], not included here, can have the effect of displacing the DAMA region away from XENON100 constraints (see text).

WIMP limits presented by the XENON100 collaboration are the least conservative choice over a present uncertainty spanning several orders of magnitude, including the very real possibility that LXe is an effectively inert detection medium for WIMPs in this low-mass range. As such, these limits are untenable. A more conservative treatment of present-day uncertainties in  $\mathcal{L}_{\text{eff}}$  (such as for instance, that adopted by the ZEPLIN collaboration [6]) would also lead to weaker limits at higher WIMP masses, raising an additional question on the relevance of the present XENON100 sensitivity in comparison to that from CDMS and other experiments.

The onus of unequivocally demonstrating the existence of scintillation light from  $\sim 1 \text{ keV}_r$  recoils in LXe is on the XENON100 collaboration. Attempts to substitute for this with a biased analysis represent a lack of consideration for the many efforts made by other dark matter researchers working towards similar ends. We invite the XENON100 collaboration to reconsider their claims, and to include in all future results a balanced description of the many unknowns and the uncertainty they represent.

The authors are indebted to E. Dahl for many useful comments, and to A. Manzur for the preparation of Fig. 1.

## I. APPENDIX

Figs. 4 and 5 illustrate the dependence on the specific  $\mathcal{L}_{\text{eff}}$  model used for the extraction of light-WIMP limits from XENON100 data. We have followed the procedure described in [1], allowing the sensitivity to be dominated by a Poisson tail of photoelectrons generated from recoils from the low-energy region for which experimental calibration data do not exist. While we do not condone this approach, it allows us to isolate the effect of the choice of  $\mathcal{L}_{\text{eff}}$  model. Given the very specific meaning of the Co-GeNT region showed in [1] (which is explicitly mentioned in [3]), we use experiment regions and astrophysical parameters as in Fig. 1 in [20] for these calculations. We obtain excellent agreement with the sensitivity claimed by XENON100 above  $\sim 7 \text{ GeV}/c^2$ , when using their flat  $\mathcal{L}_{\text{eff}}$  low-energy extrapolation and the favorable astrophysical parameters employed by them (such as  $\rho_{DM} = 0.5 \text{ GeV}/\text{cm}^3$  and  $v_{esc} = 650 \text{ km/s}$ ). However, we do not reproduce the unexpected power-law behavior of their limit

curve that is evident at lower masses, even when taking into account S1 fluctuations.

To establish a comparison with other models, we fit the recent data from Manzur *et al.* [5] with an adiabatic term as in [10], to account for the expected kinematic cutoff for LXe ( $E_{max}$ ). A similar decrease in  $\mathcal{L}_{\text{eff}}$  at low energies is predicted by the model presented in [5], which takes into account the effect of electrons that escape the nuclear recoil track, and thus do not recombine to produce scintillation. ZEPLIN data are better fitted by a logistic (sigmoid) function. Both choices (adiabatic and logistic) are conservative in the sense that they generate a finite amount of scintillation all the way down to zero energy, something for which there is no experimental evidence at the present time. For the astrophysical parameters used here, the adiabatic fit to Manzur *et al.*, and a  $7 \text{ GeV}/c^2$  WIMP with  $5 \times 10^{-41} \text{ cm}^2$  spin-independent coupling, we would expect 0.045 events above a 4 photoelectron threshold for the XENON100 data set. This becomes 0.25 events for a 3 photoelectron threshold.

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